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DOI: <https://doi.org/10.1209/0295-5075/91/47005>

Posted at the Zurich Open Repository and Archive, University of Zurich

ZORA URL: <https://doi.org/10.5167/uzh-45363>

Journal Article

Accepted Version

Originally published at:

Weyeneth, S; Bendele, M; Puzniak, R; Murányi, F; Bussmann-Holder, A; Zhigadlo, N D; Katrych, S; Bukowski, Z; Karpinski, J; Shengelaya, A; Khasanov, R; Keller, H (2010). Field-dependent superfluid density in the optimally doped SmFeAsO_{1-x}Fy superconductor. EPL (Europhysics Letters), 91(4):47005. DOI: <https://doi.org/10.1209/0295-5075/91/47005>

Field Dependent Superfluid Density in the Optimally Doped $\text{SmFeAsO}_{1-x}\text{F}_y$ Superconductor

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PACS 74.70.Xa – Pnictides and chalcogenides

PACS 74.25.Ha – Magnetic properties including vortex structures and related phenomena

PACS 76.75.+i – Muon spin rotation and relaxation

PACS 74.25.Bt – Thermodynamic properties

Abstract. - The magnetic field dependence of the in-plane magnetic penetration depth λ_{ab} for optimally doped $\text{SmFeAsO}_{1-x}\text{F}_y$ was investigated by combining torque magnetometry, SQUID magnetometry, and muon-spin rotation. The results obtained from these techniques show all a pronounced decrease of the superfluid density $\rho_s \propto \lambda_{ab}^{-2}$ as the field is increased to 1.4 T. This behaviour of ρ_s is analysed within a two-band model with self-consistently derived coupled gaps and $\rho_s = \rho_{s1} + \rho_{s2}$, where ρ_{s1} related to the larger gap is field independent, and ρ_{s2} related to the smaller gap is strongly suppressed with increasing field.

After the discovery of superconductivity in $\text{LaFeAsO}_{1-x}\text{F}_x$ [1] with a transition temperature $T_c \simeq 26$ K, a whole new family of iron-based superconductors was found with a maximum $T_c \simeq 55$ K for $\text{SmFeAsO}_{1-x}\text{F}_y$ [2], where $y \leq x$ due to a possible oxygen deficiency in the chemical composition [3]. Various experiments indicate multi-gap superconductivity within the family $\text{REFeAsO}_{1-x}\text{F}_y$ (RE = rare-earth element) [3–8]. Furthermore, the magnetic penetration depth anisotropy, $\gamma_\lambda = \lambda_c/\lambda_{ab}$, increases with decreasing temperature, in contrast to the upper critical field anisotropy, $\gamma_H = H_{c2}^{||ab}/H_{c2}^{||c}$, which decreases with decreasing temperature [9–11], similar to those of the two-gap superconductor MgB_2 [12, 13], although with reversed slopes [14–16]. Here λ_i and $H_{c2}^{||i}$ denote the magnetic penetration depth and the upper critical field components along the crystallographic direction i (ab -plane or c -axis).

Besides of the influence of the magnetic field H and temperature T on the anisotropy, the direct influence of H and T on λ is essential in probing multi-gap supercon-

ductivity [17]. However, it is difficult to obtain reliable experimental evidence for multi-gap superconductivity from the temperature dependence of λ in samples containing magnetic ions such as $\text{SmFeAsO}_{1-x}\text{F}_y$. Importantly, the superfluid density $\rho_s = n_s/m^*$, with n_s being the superfluid carrier density and m^* the effective carrier mass, can be probed directly by measuring $\lambda^{-2} \propto \rho_s$.

In the two-gap superconductor MgB_2 [17] ρ_s was found to be field dependent due to a suppression of the superfluid density in the band with the smaller gap [18, 19]. A similar dependence was observed for NbSe_2 [20, 21], V_3Si [22], $\text{YNi}_2\text{B}_2\text{C}$ [23], and $\text{La}_{1.83}\text{Sr}_{0.17}\text{CuO}_4$ [24] and again suggested to stem from either multi-gap superconductivity or to be related to changes of the internal field distribution of the vortex lattice.

Previous studies of λ_{ab} in $\text{LaFeAsO}_{1-x}\text{F}_x$ [25] and in SmFeAsO_{1-x} and NdFeAsO_{1-x} [26] by muon-spin rotation (μSR) experiments indicated a field dependent ρ_s up to 0.6 T in the $\text{REFeAsO}_{1-x}\text{F}_y$ family. Also in the related $\text{Ba}(\text{Fe}_{0.926}\text{Co}_{0.074})_2\text{As}_2$ compound a field dependent ρ_s was reported for fields up to 0.2 T [27], and being interpreted in terms of multi-gap superconductivity. However,

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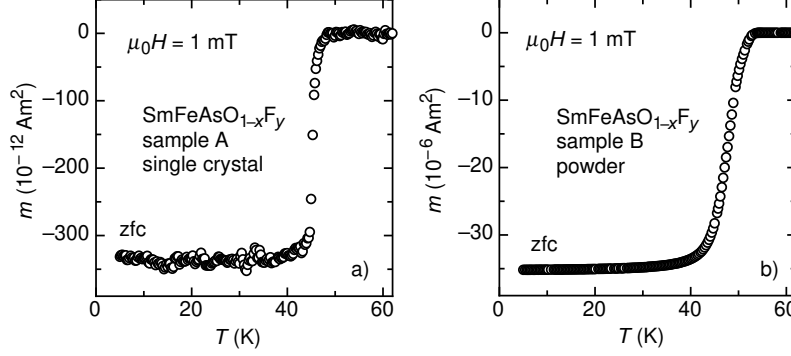


Fig. 1: Measured magnetic moment m of $\text{SmFeAsO}_{1-x}\text{F}_y$ as a function of temperature T in 1 mT magnetic field: a) single-crystal sample A, b) powder sample B. The rather sharp transition at T_c demonstrates the good quality of our samples.

high field investigations of $\text{SmFeAsO}_{0.8}\text{F}_{0.2}$ single crystals between 3 T and 30 T infer a field independent ρ_s for $\text{SmFeAsO}_{1-x}\text{F}_y$ [28]. This obvious controversy is clarified in this letter by extended investigations of the magnetic field dependence of λ_{ab} in the $\text{SmFeAsO}_{1-x}\text{F}_y$ system. As the magnetic penetration depth λ_{ab} derived from μSR data must be carefully evaluated in order to demonstrate that the observed magnetic field dependence of ρ_s is intrinsic and not influenced by artificial contributions from the magnetic field distribution, additional experimental methods to investigate λ_{ab} are desired. Magnetisation as a global probe is less sensitive to the microscopic details of the magnetic field distribution inside a superconductor which is measured in μSR experiments. Additionally in magnetic torque experiments λ_{ab} is measured in terms of the average torque amplitude and almost insensitive to vortex pinning effects. Thus, a combination of magnetic and μSR experiments is eligible to provide convincing experimental evidence for the magnetic field dependence of λ_{ab} . Here, we report on a combined magnetic torque, SQUID magnetisation, and μSR study of the magnetic penetration depth, evidencing a pronounced magnetic field dependence of λ_{ab} in optimally doped $\text{SmFeAsO}_{1-x}\text{F}_y$ up to 1.4 T.

In this work single crystal and powder $\text{SmFeAsO}_{1-x}\text{F}_y$ samples were used, both of them synthesised by high-pressure techniques [3, 29]. During the growth process, the composition $\text{SmFeAsO}_{1-x}\text{F}_y$ was fine tuned by varying x and y , in order to achieve a doping level close to optimal [3]. The single crystal of nominal composition $\text{SmFeAsO}_{0.8}\text{F}_{0.2}$ (sample A) with an onset of $T_c \simeq 47$ K had approximate dimensions of $90 \times 80 \times 5 \mu\text{m}^3$. The powder sample of nominal composition $\text{SmFeAsO}_{0.85}\text{F}_{0.15}$ (sample B) with an onset of $T_c \simeq 54$ K was pressed into a pellet of cylindrical shape with 4 mm diameter and 2 mm height. Both samples were characterised by X-ray diffraction with similar properties as reported earlier [3, 29]. Figure 1 displays the low-field magnetic moment m of sample A and B, measured in a SQUID magnetometer MPMS-XL (*Quantum Design*) using the

reciprocating sample option (RSO) with $\mu_0 H \simeq 1$ mT in zero-field cooled (zfc) mode [3, 29]. Both samples exhibit ideal diamagnetism at low temperature. The transition width (defined by the temperature range between 10% and 90% of ideal diamagnetism observed in the zfc low-field $m(T)$ curve) is found to be 2 K and 6 K for the samples A and B, respectively, which demonstrates the good quality of the samples studied here.

The single crystal sample A was investigated by torque magnetometry in order to determine $\lambda_{ab}(H)$. All measurements were performed using a custom-made torque magnetometer, previously employed to determine the anisotropic properties of tiny single crystals of iron pnictides [9, 10]. The magnetic torque $\vec{\tau} = \mu_0(\vec{m} \times \vec{H})$, related to the magnetic moment \vec{m} , was recorded as a function of the angle θ between the magnetic field \vec{H} and the c -axis of the crystal. During the measurement, H was rotated clock- and counter clockwise around the sample at constant temperature T . Due to the present irreversibility, a vortex-shaking technique [9, 30] was applied with a 200 Hz electromagnetic field of a few mT perpendicular to H . The clockwise (θ^+) and counter clockwise (θ^-) torque scans were averaged according to $\tau_{\text{rev}}(\theta) = [\tau(\theta^+) + \tau(\theta^-)]/2$, in order to further diminish irreversibility effects. A small sinusoidal normal state background of anisotropic paramagnetic origin was subtracted from all data by a symmetrising procedure [10, 28].

A theoretical expression for the angular dependence of the torque, involving the two anisotropy parameters γ_λ and γ_H independently, was derived within Ginzburg-Landau theory by Kogan [31]:

$$\begin{aligned} \tau(\theta) = & -\frac{V\Phi_0 H}{16\pi\lambda_{ab}^2} \left(1 - \frac{1}{\gamma_\lambda^2}\right) \frac{\sin(2\theta)}{\epsilon_\lambda} \\ & \cdot \left[\ln \left(\frac{\eta H_{c2}^{\parallel c}}{H} \frac{4e^2 \epsilon_\lambda}{(\epsilon_\lambda + \epsilon_H)^2} \right) \right. \\ & \left. - \frac{2\epsilon_\lambda}{\epsilon_\lambda + \epsilon_H} \left(1 + \frac{\epsilon'_\lambda}{\epsilon'_H}\right) \right]. \end{aligned} \quad (1)$$

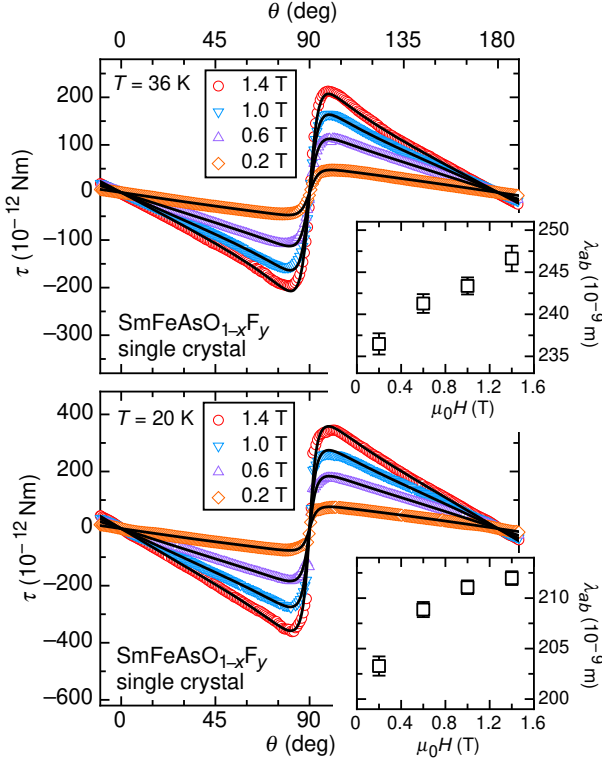


Fig. 2: (Colour online) Reversible torque for the single crystal $\text{SmFeAsO}_{1-x}\text{F}_y$ (sample A), measured at 36 K and 20 K in various magnetic fields. Solid lines are calculated using Eq. (1), from which λ_{ab} was extracted. The inserts show the magnetic field dependence of λ_{ab} .

Here Φ_0 is the magnetic flux quantum and V the volume of the crystal. The scaling function $\epsilon_i(\theta) = [\cos^2(\theta) + \gamma_i^{-2} \sin^2(\theta)]^{1/2}$ with $i = \lambda, H$ is different for γ_λ and γ_H , and $\epsilon'_i(\theta)$ denotes the derivative with respect to θ . The torque data were analysed with Eq. (1). From earlier work [9,10] the temperature dependence of $H_{c2}^{\parallel c}$ was determined, and the anisotropy parameters were found to be field independent up to 1.4 T. Since Eq. (1) contains multiple correlated parameters, making a simultaneous analysis of all quantities difficult, all parameters except λ_{ab} were kept fixed in the studied field range at the same values reported in [10], thereby reducing the scattering of λ_{ab} . Because, upper critical fields in optimally doped $\text{SmFeAsO}_{1-x}\text{F}_y$ are reported to exceed tens of Tesla [3, 4, 28], this restriction to fix $H_{c2}^{\parallel c}$ for different H at the same temperature during the data analysis appears reasonable since the field distribution of the vortex lattice at such low magnetic fields is close to the London limit. Representative experimental torque data collected at two temperatures and various magnetic fields together with the calculated curves [Eq. (1)] are presented in Fig. 2. At 20 K and 36 K λ_{ab} increases substantially with increasing magnetic field (see inserts to Fig. 2). For $T < 20$ K the presence of disturbing pinning effects [9] made the analysis meaningless, while for $T > 36$ K the torque signal was too weak to ex-

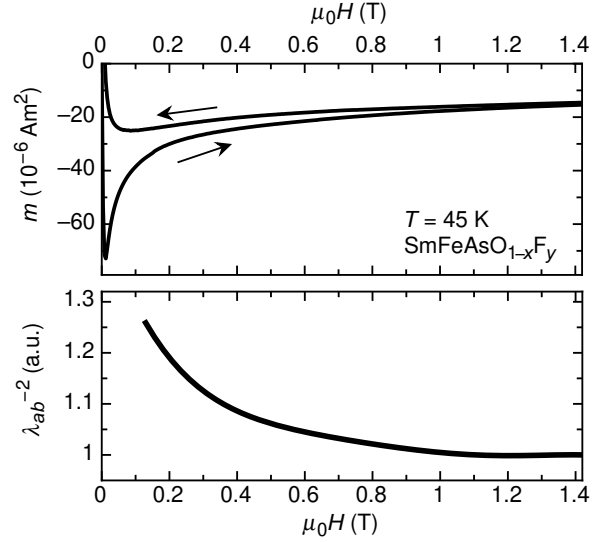


Fig. 3: Results of the SQUID investigation for sample B (powder) of $\text{SmFeAsO}_{1-x}\text{F}_y$. Upper panel: Field dependence of the magnetic moment m at 45 K measured for increasing and decreasing magnetic field. Lower panel: Field dependence of λ_{ab}^{-2} derived by Eq. (2).

tract reliable values of λ_{ab} , especially in the relevant low field regime.

Additional SQUID magnetisation and μSR investigations were performed on the larger powder sample (sample B). For anisotropic layered superconductors the effective magnetic penetration depth λ_{eff} of unoriented powder samples can be related to λ_{ab} via $\lambda_{\text{eff}} \simeq 1.31\lambda_{ab}$ [32]. For optimally doped $\text{SmFeAsO}_{1-x}\text{F}_y$ we find values of γ_λ , exceeding 7 at T_c and increasing to 19 at zero temperature [9,10], thus confirming this approximation and being in accordance with other experiments which reveal comparable values for γ_λ in related compounds [28,33]. Field dependent SQUID measurements of the magnetic moment at 45 K are shown in the upper panel of Fig. 3. The analysis of these data is based on the average of the magnetisation for increasing and decreasing magnetic field with λ_{ab}^{-2} being derived as [17]

$$\lambda_{ab}^{-2} \propto \frac{\partial m}{\partial \ln(H)} = H \frac{\partial m}{\partial H}. \quad (2)$$

From Eq. (2) λ_{ab}^{-2} was determined and is shown in the lower panel of Fig. 3. Obviously, λ_{ab}^{-2} at 45 K decreases continuously as the field is increased up to 1.4 T, in good agreement with the torque result (see Fig. 4).

In order to substantiate our main result on the magnetic field dependence of λ_{ab} obtained on single crystals, the powder sample B was further studied by transverse-field (TF) and longitudinal-field (LF) μSR at the Paul Scherrer Institute (PSI) (For detailed information on the TF and LF μSR techniques see *e.g.* [34]). Previous μSR investigations of $\text{REFeAsO}_{1-x}\text{F}_y$ [26, 35–37] indicate that: (i) The muons stop at two lattice sites, one is close to

the magnetic moments of the Fe ions in the FeAs layers, whereas the other is near the spacing layers containing the rare-earth ions [26, 35, 36]. (ii) The magnetic moments of the Sm ions order antiferromagnetically at temperatures below ~ 5 K, leading to a pronounced local-field broadening of the magnetic field distribution [26, 36]. In addition, for temperatures above 5 K the finite correlation of the magnetic moments leads to thermally activated spin-fluctuations and causes a damping of the TF time spectra [26, 37]. (iii) Consistent with the above two points, the μ SR time spectra of $\text{SmFeAsO}_{1-x}\text{F}_y$ consist of a slow and a fast relaxing component [35, 36]. Combining these three points and invoking, according to calculations by Hayano *et al.* [38], the magnetic correlation of the Sm moments to be similar in LF and TF experiments, the total transverse-field asymmetry $A(t)$ of the time evolution of the muon-spin polarisation in $\text{SmFeAsO}_{1-x}\text{F}_y$ can be written as [26]

$$A(t) = (A_s e^{-\Lambda_s t} + A_f e^{-\Lambda_f t}) e^{-\sigma^2 t^2 / 2} \cos(g_\mu B t + \phi). \quad (3)$$

Here A_s (A_f) and Λ_s (Λ_f) are the asymmetry and the depolarisation rate of the slow (fast) relaxing component, respectively, B is the magnetic induction at the muon sites, g_μ is the muon gyromagnetic ratio, ϕ is the initial phase of the muon-spin ensemble, and σ is the Gaussian measure of the second moment of the magnetic field distribution within the sample.

All μ SR time spectra were fitted simultaneously by Eq. (3) with the ratio A_s/A_f as a common parameter and Λ_s and Λ_f as individual parameters for each data set. The total asymmetry $A_s + A_f$ was kept constant within each set of the data. The temperature dependent depolarisation rates Λ_s and Λ_f in Eq. (3) are both assumed to have the form [26]

$$\frac{1}{\Lambda_i(T)} = \frac{1}{\Lambda_i(0)} + C \exp(-E_0/k_B T), \quad i = s, f, \quad (4)$$

with E_0 being the activation energy for both relaxations and C a constant. Our analysis yields $\Lambda_s(0) \simeq 0.20(5) \mu\text{s}^{-1}$, $\Lambda_f(0) \simeq 2.71(7) \mu\text{s}^{-1}$, and $E_0 \simeq 20(1) \text{ meV}$. This procedure includes the background contribution due to the correlation of the Sm magnetic moments. Since the Sm moments order antiferromagnetically below ~ 5 K [26, 36], an analysis for $T \leq 10$ K was omitted in this work. From Eq. (3) the two-component Gaussian relaxation rate σ was obtained: $\sigma = (\sigma_{\text{sc}}^2 + \sigma_{\text{nm}}^2)^{1/2}$, where σ_{nm} is the temperature independent nuclear moment contribution, and σ_{sc} is the superconducting relaxation rate due to the muon-spin depolarisation in the vortex lattice [26]. The values of $\lambda_{ab} \simeq \lambda_{\text{eff}}/1.31$ were derived from σ_{sc} according to [39]

$$\sigma_{\text{sc}} [\mu\text{s}^{-1}] = 4.83 \times 10^4 (1 - H/H_{c2}) \cdot \left[1 + 1.21 \left(1 - \sqrt{H/H_{c2}} \right)^3 \right] \lambda_{\text{eff}}^{-2} [\text{nm}], \quad (5)$$

with the same values of H_{c2} as used for the torque experiment. The magnetic field dependence of λ_{ab}^{-2} , derived

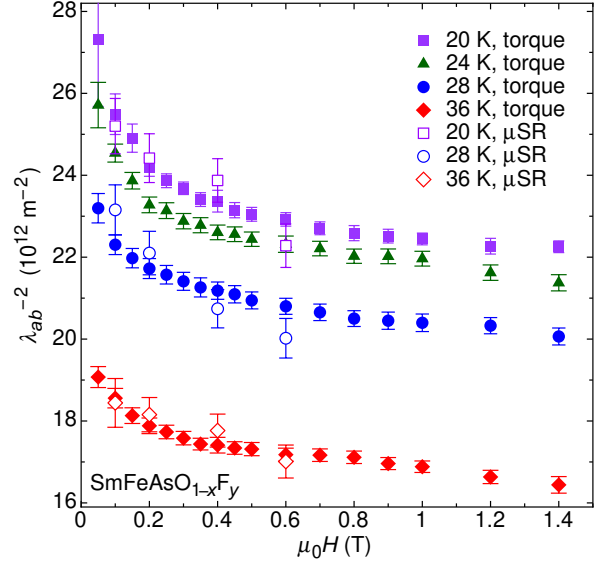


Fig. 4: (Colour online) Field dependence of $\lambda_{ab}^{-2} \propto \rho_s$ of $\text{SmFeAsO}_{1-x}\text{F}_y$ derived from the magnetic torque (sample A, closed symbols) and μ SR (sample B, open symbols) experiments.

from the μ SR data together with the results from extended torque studies, are presented in Fig. 4. Evidently, λ_{ab}^{-2} is substantially suppressed with increasing magnetic field at all temperatures studied and follows, when normalised to $\lambda_{ab}^{-2}(1.4 \text{ T}/\mu_0)$, on a universal curve (see Fig. 5).

The present results as obtained from all three techniques demonstrate very clearly a decrease of λ_{ab}^{-2} with increasing magnetic field. From Figs. 3, 4, and 5 we estimate a suppression of the superfluid density by 20% when the field increases from 0 T up to 1.4 T. Assuming a single-gap scenario, for $H \ll H_{c2}^{\parallel c}$, only a nodal superconductor is expected to show a field dependent superfluid density [25, 26, 37, 40]. Since however $\text{SmFeAsO}_{1-x}\text{F}_y$ is nodeless [8, 41], alternative explanations need to be considered. An influence of H_{c1} on the determination of λ_{ab}^{-2} can be excluded, since for an estimated value of $\lambda_{ab}(0) \simeq 200 \text{ nm}$ the corresponding $H_{c1}^{\parallel c}(0) \propto \lambda_{ab}^{\parallel c}(0)$ is of the order of 0.05 T, well below the lowest field studied here. A systematic error in the determination of λ_{ab} caused by pinning appears to be unlikely as well: (i) In SQUID magnetometry pinning contributes strongly at low temperatures. The field dependence of the magnetic moment was performed at 45 K, where pinning effects are considerably reduced. (ii) In the μ SR experiments all data were obtained in field cooled vortex-lattice states. From the field dependence of the magnetic field distribution in the mixed state, a distortion of the μ SR spectra caused by pinning can be excluded [26]. (iii) In the torque experiment, a shaking technique was applied in order to minimise irreversibility effects [30]. Thus, the determination of λ_{ab} is not affected by pinning. Furthermore, the derived λ_{ab} is mainly susceptible to the average torque amplitude which is almost insensitive to

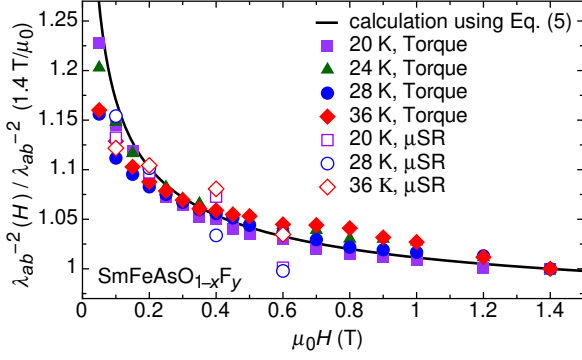


Fig. 5: (Colour online) Universal behaviour of ρ_s observed for both samples (A and B) of $\text{SmFeAsO}_{1-x}\text{F}_y$ for all investigated temperatures, normalised to its value at the maximum field of 1.4 T. The black line is calculated using Eq. (6). The meaning of the symbols is the same as in Fig. 4

pinning, in contrast to $H_{c2}^{\parallel c}$, which was fixed during the data analysis [9, 10].

As already mentioned above, the observed magnetic field dependence of λ_{ab}^{-2} is absent in nodeless single-gap superconductors [42] but has been observed in various multi-band superconductors, where the cases of MgB_2 [17–19] and $\text{La}_{1.83}\text{Sr}_{0.17}\text{CuO}_4$ [24] have been analysed in detail. The analogy to these systems suggests that related physics apply here as well. Assuming that $\text{SmFeAsO}_{1-x}\text{F}_y$ is a fully-gapped superconductor [8, 41], a two-gap model [43] is used to calculate the superfluid density $\rho_s = \rho_{s1} + \rho_{s2}$, stemming from the coupled gaps (Δ_1, Δ_2) . In this approach, the zero-temperature gaps are calculated self-consistently in relation to the total superfluid density ρ_s . The best agreement is found by fixing the values $\Delta_1(0) = 13.83$ meV and $\Delta_2(0) = 5.26$ meV, close to the s-wave gap values as obtained by point-contact spectroscopy [6, 7], performed on samples from the same source [29]. With increasing magnetic field the superfluid density is mainly suppressed in the band with the small gap (ρ_{s2}, Δ_2) where the corresponding intra-band interaction approaches zero with increasing field. Note however, that the gap itself is not zero due to finite inter-band interactions analogous to MgB_2 [18, 19]. The total superfluid density $\rho_s(H)$ is expressed as a sum of a contribution from the band with the large gap, ρ_{s1} , which is independent of the field, and a field dependent contribution from the band with the small gap, $\rho_{s2} \propto 1/\sqrt{H}$. The field independence of ρ_{s1} stems from the same physics as in MgB_2 [18, 19] and the $1/\sqrt{H}$ dependence of $\rho_{s2}(H)$ is based on the multi-gap analysis of $\text{La}_{1.83}\text{Sr}_{0.17}\text{CuO}_4$, where the coupled gaps have different field dependencies, namely, the d-wave gap being proportional to \sqrt{H} [44] and the s-wave gap having a $1/\sqrt{H}$ dependence [45]. Since the s-wave symmetry of the $\text{SmFeAsO}_{1-x}\text{F}_y$ superconductor is well justified [8], the $1/\sqrt{H}$ dependence is plausible. Thus, the expression

$\rho_s(H)/\rho_{s1}$ is derived as

$$\rho_s(H)/\rho_{s1} = 1 + C(H/H_0)^{-1/2}/\rho_{s1}, \quad (6)$$

where C denotes the amplitude of $\rho_{s2}(H)$ and H_0 is the characteristic field for suppressing ρ_{s2} . A fit to the normalised superfluid density data by Eq. (6) leads to an estimation of $(C/\rho_{s1})^2\mu_0 H_0 \simeq 6.1$ mT. The calculated result is shown in Fig. 5, in comparison with the normalised data, with obviously good agreement between both.

It is important to emphasise that although ρ_s is suppressed by 20% in small fields, T_c is almost not changing on the same field scale, consistent with high values of H_{c2} . This can be understood in terms of a suppression of the intra-band coupling within the band of the small gap, having a pronounced influence on the corresponding ρ_s , but almost no effect on T_c [18, 19].

In conclusion, we observe a magnetic field dependence of the superfluid density in the iron-pnictide superconductor $\text{SmFeAsO}_{1-x}\text{F}_y$. This experimental observation can be consistently described within a coupled two-gap model, where the superfluid density related to the large gap is field independent, whereas the one of the small gap is strongly suppressed with increasing magnetic field. Together with the temperature dependence of the anisotropy parameters, multi-gap superconductivity is well reflected in the thermodynamic behaviour of $\text{SmFeAsO}_{1-x}\text{F}_y$.

We thank S. Strässle for his help in preparing the manuscript and B. M. Wojek for helpful discussions and useful comments. This work was in part performed at the $\text{S}\mu\text{S}$ at Paul Scherrer Institute (Switzerland) and was partially supported by the Swiss National Science Foundation, the NCCR program MaNEP, the Polish Ministry of Science and Higher Education, within the research project for the years 2007-2010 (No. N N202 4132 33), and the Georgian National Science Foundation grant GNSF/ST08/4-416.

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